Evaluation of the impact of different frequency dependent soil models on lightning overvoltages

Marco Aurélio O. Schroeder a,⁎, Maria Teresa Correia de Barros b, Antonio C.S. Lima c, Márcio M. Afonso d, Rodolfo A.R. Moura a,c

⁎ Corresponding author.

E-mail addresses: schroeder@ufsj.edu.br (M.A.O. Schroeder),
teresa.correia@barros@tecniico.ulisboa.pt (M.T.C. de Barros), acl@dee.ufsj.br
(A.C.S. Lima), marciomattias@des.cefetmg.br (M.M. Afonso), moura@ufsj.edu.br
(R.A.R. Moura).

http://dx.doi.org/10.1016/jEPSR.2017.09.020
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1. Introduction

Direct lightning strikes are a frequent cause of transmission line outages. As well detailed in Ref. [1], when a stroke hits a tower, a portion of the current travels down the tower and the remainder portion goes through the shield wires. The tower current flows to earth at the tower base through the grounding system. The resultant voltage wave reflected back up to the tower top depends directly on the value of the footing impedance encountered by the current. A sufficiently high voltage may stress the insulator strings and result in backflashover. According to Ref. [1]: “Since the tower voltage is highly dependent on the footing impedance, it follows that footing impedance is an extremely important factor in determining lightning performance”.

The overvoltages on transmission lines yielded by direct lightning strikes are usually computed by using simplified analytical approaches or by simulations using full electromagnetic models or EMT-type programs [1–9]. The use of simplified analytical approaches should be avoided, since they consider certain assumptions that could lead to errors in estimating the lightning performance of transmission lines. The use of full electromagnetic models, although they provide the most accurate results, has the drawback of being very computational time consuming. On the other hand, the widespread EMT-type programs have several models of the electrical system components that allow in most cases a sufficient accurate analysis of the lightning overvoltages propagation along transmission lines. However, EMT-type programs usually do not have accurate models to represent the lightning response of grounding, including its wideband behaviour.

As already mentioned, the grounding system is an extremely important component in determining lightning performance of transmission lines [10]. Nevertheless, in most evaluations consid-
erating simplified approaches or EMT-type programs, the grounding is represented by a simple resistance [1–6, 11–13]. Such representation disregards some effects that arise when the grounding is subjected to lightning currents, for instance, capacitive and inductive effects along with propagation phenomena [11, 14]. Also, even when more elaborate models are used for grounding representation, the frequency dependence of soil parameters is not included in evaluations [7–8]. However, according to recent experimental works, disregarding the frequency dependence of soil parameters can lead to significant errors on estimating the lightning performance of grounding electrodes [12, 15–17].

The impact of the frequency dependence of soil parameters on the lightning performance of transmission lines was recently addressed in Ref. [9], where an accurate representation of grounding systems and transmission line is presented [18]. However, application of the Hybrid ElectroMagnetic (HEM) model to simulate the entire transmission system results into a large computation effort.

The aim of this paper is to present an efficient solution allowing interfacing a wideband modeling of grounding systems with EMT-type programs in order to accurately assess the influence of grounding frequency behaviour on developed overvoltages across insulators. Furthermore, the impact of the frequency dependence of soil on the developed overvoltages on transmission lines due to direct lightning strokes is addressed.

2. Frequency dependence of soil parameters

According to classical laboratory measurements, there is a significant frequency dependence of soil resistivity \( \rho \) and permittivity \( \varepsilon \) in the representative frequency range of lightning currents [19–21]. In spite of the knowledge of such frequency dependence of soil parameters, it had been neglected until recently in studies evaluating the lightning performance of grounding systems, probably due to the lack of an accurate general formulation to describe it. According to Ref. [15], in a conservative approach, soil resistivity is assumed as the value measured by conventional measuring instruments, which employ low-frequency signals. In the same approach, soil relative permittivity is assumed to vary from 4 to 81, according to the soil humidity, being very common to assume values between 10 and 20.

In this paper it is analysed the impact of considering the variation with the frequency in the overvoltages developed at the point of current injection in the grounding (Grounding Potential Rise) and in the insulator strings. For this, three formulations are considered, an older one [21] and two more recent [15, 22]. These works are briefly presented in the following subsections.

2.1. Formulations of R. Alipio and S. Visacro

Recently, R. Alipio and S. Visacro proposed Eqs. (1) and (2) to compute the frequency dependence of soil conductivity \( \sigma \) and relative permittivity \( \varepsilon \) based on a large number of field measurements and on the causal Kramers–Kronig’s relationships and Maxwell Equations [22].

\[
\sigma = \sigma_0 + \sigma_0 \cdot h(\sigma_0) \left( \frac{f}{1 \text{ MHz}} \right)^\gamma \tag{1}
\]

\[
\varepsilon_r = \varepsilon_{\infty} + \frac{\tan \left( \frac{\pi \gamma}{2} \right) \times 10^{-3}}{2 \pi \sigma_0 \left( 1 \text{ MHz} \right)^\gamma} \sigma_0 \cdot h(\sigma_0) f^\gamma \tag{2}
\]

In Eqs. (1) and (2), \( \sigma \) is the soil conductivity in mS/m, \( \sigma_0 \) is the low-frequency conductivity (100 Hz) in mS/m, \( \varepsilon_r \) is the relative permittivity, \( \varepsilon_{\infty} \) is the relative permittivity at higher frequencies, \( \varepsilon_0 \) is the vacuum permittivity \( (\varepsilon_0 \approx 8.854 \times 10^{-12} \text{ F/m}) \) and \( f \) is the frequency in Hz. The parameters \( h(\sigma_0), \gamma \) and \( \varepsilon_{\infty} \) are given by Eq. (3) in order to obtain mean results for the frequency dependence of soil parameters, as detailed in Ref. [22].

\[
h(\sigma_0) = 1.26 \times \sigma_0^{0.73} \tag{3a}
\]

\[
\gamma = 0.54 \tag{3b}
\]

\[
\varepsilon_{\infty} = 12 \tag{3c}
\]

It is worth mentioning that the consistency of such expressions to compute the frequency dependence of soil parameters was proved based on experimental results [22].

2.2. Formulations of C. M. Portela

C. M. Portela carried out a series of measurements which comprises experimental data obtained in several geographical areas in Brazil and considers soil samples measured from 100 Hz up to 2 MHz. The value of the effective conductivity \( \sigma \), as well as relative permittivity, is expressed as a function of the low frequency conductivity \( \sigma_0 \) obtained from the measured 100 Hz soil resistivity, according to Eq. (4).

\[
\sigma = \sigma_0 + \sigma_0 \left[ \cot \left( \frac{\pi}{2} \frac{\omega}{2 \pi \times 10^6} \right) \frac{\omega}{2 \pi \times 10^6} \right] \tag{4}
\]

where \( \omega \) is the angular frequency, \( \sigma_0 = 1/\rho_0 \) (where \( \rho_0 \) is the low frequency ground resistivity). \( \Delta \omega \) and \( \omega \) are statistical parameters, which express the frequency dependence of soil conductivity and permittivity. To evaluate the probability density functions associated with parameters \( \Delta \omega \) and \( \omega \), Weibull distributions were adopted. As discussed in Ref. [15], for most cases of interest, it may be acceptable to consider median values for both \( \Delta \omega \) and \( \omega \), which are 11.71 S/m and 0.706 respectively.

2.3. Formulations of C. L. Longmire and K. S. Smith

In 1975, C. L. Longmire and K. S. Smith published a paper with a general formulation to compute the frequency dependence of the soil’s impedance based on the idea that a differential volume of the soil, named “universal soil”, can be represented by a RC net [21]. The formulation is valid for frequencies in the range of 100 Hz to 1 MHz. Relative permittivity and soil conductivity are calculated by Eqs. (5) and (6), respectively.

\[
\varepsilon_r = \varepsilon_{\infty} + \sum_{n=1}^{N} \frac{a_n}{1 + (f/f_n)^2} \tag{5}
\]

\[
\sigma = \sigma_1 + 2 \pi \varepsilon_0 \sum_{n=1}^{N} \frac{a_n f_n}{1 + (f/f_n)^2} \tag{6}
\]

where \( \varepsilon_{\infty} = 5 \times (P/10)^{1.28} \times 10^{-1} \text{ Hz} \); \( a_n \) assumes the values of Table 1; \( \sigma_1 = 8 \times 10^{-3} (P/10)^{1.54} \text{ S/m} \). \( P \) is adjustable according to the value of low frequency soil resistivity [21].

Table 1

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<thead>
<tr>
<th>N</th>
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<tr>
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</tr>
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